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(54) **Liquid crystal display.**

(57) A liquid crystal display operable in normally white mode comprises a liquid crystal display panel (26). A scan line driver (24) addresses scan lines of the panel (26). A data line driver (22) applies a range of different voltages to data lines of the panel (26) to produce different gray scale levels in a gray scale picture. The data line driver (22) comprises a reference voltage circuit (28) for offsetting the range of applied voltages in such a manner that the transmittance of the panel (26) decreases substantially linearly from the lower extreme of the range to the upper extreme. By shifting the lowest applied voltage in the Voltage-Transmittance curve in the direction of monotonously decreasing area of the V-T curve, brightness or gradation is prevented from being inverted. Thus, the liquid crystal display simultaneously provides both good contrast ratios and good gradation at large viewing angles.

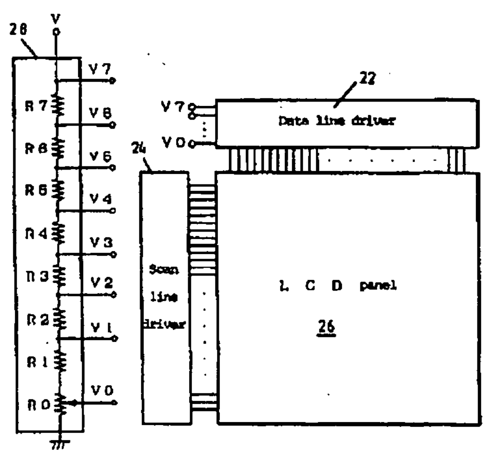

FIG. 9

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The present invention relates to a liquid crystal display for providing improved gray-scale display at wider viewing angles.

A typical active matrix-type liquid crystal display comprises a twisted nematic liquid crystal material to provide sufficient response and contrast in response to low voltage drive signals. A TN-type liquid crystal display has two display modes. One is a normally-white mode in which bright display is obtained when no voltage is applied. The other is a normally-black mode in which dark display is obtained when no voltage is applied. In the normally-black mode, the contrast ratio is decreased because colouring occurs due to the shielding of light varying as a function of the wavelength of the light. This is known as optically rotatory dispersion. However, in the normally-white mode, if sufficient voltage is applied, a good dark state can be obtained, and therefore a high contrast ratio can be implemented. Therefore normally-white mode liquid crystal displays are preferred.
Depending on whether or not the transmission axis of the polarising plate on the incidence side is set in parallel to the rubbing direction on the incidence side, each of the above modes can be subdivided into two optical modes.

In conventional normally white mode liquid crystal displays, as described in Japanese Published Unexamined Patent Applications (PUPA) No.61-121087, No.62-196625, and No.1-201622, the viewing-angle characteristics of contrast ratio and gradation have both advantages and disadvantages regardless of o or e mode. However, both good contrast ratio and good gradation cannot be simultaneously provided at a large viewing angle.

In accordance with the present invention, there is now provided a liquid crystal display operable in normally white mode, comprising: a liquid crystal display panel; a scan line driver for addressing scan lines of the panel; a data line driver for applying a range of different voltages to data lines of the panel to produce different gray scale levels in a gray scale picture; characterised in that the data line driver comprises a reference voltage circuit for offsetting the range of applied voltages in such a manner that the transmittance of the liquid crystal display panel decreases substantially linearly from the lower extreme of the range to the upper extreme.

Preferably, the panel comprises a polarising plate having incidence transmission axis parallel to incidence rubbing direction so that an extraordinary ray can be transmitted through the liquid crystal.

Viewing a second aspect of the present invention, there is now provided apparatus for driving a normally white mode liquid crystal display panel, the apparatus comprising: a scan line driver, connectable to scan lines of the panel, for addressing scan lines of the panel; a data line driver connectable to data lines of the panel for applying a range of different voltages to data lines of the panel to produce different gray scale levels in a gray scale picture; characterised in that the data line driver comprises a reference voltage circuit for offsetting the range of applied voltages in such a manner that the transmittance of the liquid crystal display panel decreases substantially linearly from the lower extreme of the range to the upper extreme.

Viewing a third aspect of the present invention, there is now provided a normally-white mode liquid crystal display apparatus, wherein gray scale displaying is obtained by providing different applied voltages corresponding to different gray scale levels, respectively, characterised in that a curve showing the relation between said applied voltages and light transmittance (thereafter called V-T curve) the lowest applied voltage is set so as to be shifted in the direction of a monotonously descreasing area of said V-T curve.

Viewing a fourth aspect of the present invention, there is now provided in a normally-white mode liquid crystal display apparatus wherein gray scale displaying is obtained by providing different applied voltages corresponding to different gray scale levels, respectively, said apparatus having applied voltage setting means for shifting the lowest applied voltage in a curve showing the relation between said applied voltages and light transmittance (thereafter called V-T curve) in the direction of a monotonously decreasing area of said V-T curve.

In a preferred embodiment of a normally-white mode liquid crystal display of the present invention, in which a gray scale picture is obtained by providing different applied voltages corresponding to different gray scale levels, in a curve relating applied voltage to transmittance (thereafter called V-T curve), the lowest applied voltage is set so as to be shifted in the direction of a monotonously decreasing area of the V-T curve. Therefore, both good contrast ratio and good gradation is obtained at wider viewing angles.

A preferred embodiment of the present invention will now be described with reference to the accompanying drawings in which:

Figure 1 is a graph showing viewing-angle dependence for light transmittance in horizontal and vertical directions;

Figure 2 is a graph showing the relation between applied voltages plotted for each angle in an upward direction and relative light transmittance;

Figure 3 is a diagram of two optical modes of a liquid crystal display;

Figure 4 is a graph showing viewing-angle dependence for relative light transmittance in e

mode;

Figure 5 is a graph showing viewing-angle dependence for relative light transmittance in o mode;

Figure 6 is a graph showing viewing-angle dependence for contrast ratios in e mode;

Figure 7 is a graph showing viewing-angle dependence for contrast ratios in o mode;

Figure 8 is a graph showing ratio of light transmittance (gray scale G0) corresponding to voltage V0 to light transmittance (gray scale G7) corresponding to voltage V7 in comparing o mode with e mode; and

Figure 9 is a block diagram of liquid crystal display apparatus of the present invention.

Referring first to Figure 3, if transmission axis 12 of a polarised plate on the incidence side is set in parallel to rubbing direction 14 on the incidence side, an extraordinary ray is transmitted through the liquid crystal. Therefore, the mode in which such an extraordinary ray transmits is called extraordinary-ray dominant mode. If transmission axis 12 of the polarising plate on the incidence side is set to make a right angle with rubbing direction 14 on the incidence side, an ordinary ray is transmitted through the liquid crystal. Therefore, the mode in which such an ordinary ray transmits is called ordinary-ray dominant mode. The rubbing direction on the output side is denoted by 16.

In the following, the viewing-angle dependence of light transmittance and contrast ratio of the normally-white mode liquid crystal display with, for example, eight-level gray scales, in the extraordinary-ray dominant mode (hereinafter called e mode) and in the ordinary-ray dominant mode (hereinafter called o mode) will be compared. The gray scales are G7 to G0 from the brightest level to the darkest level and corresponding to voltages V0 to V7 (for example, 0 to 5 volts).

Figure 4 shows viewing-angle dependence for relative light transmittance in the e mode. The left-hand graph shows viewing-angle dependence in the horizontal direction (50), and the right-hand graph shows viewing-angle dependence in the vertical direction (50). For the purposes of explanation, in the horizontal direction, the right and left directions will hereinafter be referred as positive and negative directions, respectively. Similarly, in the vertical direction, the upward and downward directions will hereinafter be referred to as positive and negative directions, respectively.

Referring to Figures 4 and 5, and particularly to the viewing-angle characteristic of transmittance (T) in the upward viewing direction in the e mode, curve V0 is below curve V1 in excess of +25 upwardly. Application of voltage V0 may be expected to maximise transmittance. However, voltage V0 does not maximise transmittance in excess of +25 upwardly. Instead, voltages V1 and V2 cause higher transmittance than V0. The loss in correspondence between applied voltage levels and gray scale levels will hereinafter be called, for convenience of explanation, "brightness inversion" or "gray-scale inversion". The viewing-angle characteristic of transmittance in o mode has a similar tendency. However, comparing o mode with e mode, the former is better in the vertical direction. However, comparing viewing-angle characteristics of transmittance in right and left directions in o mode with that in e mode, both o and e modes are good, but the latter is slightly better than the former. The range of viewing angles within which gray-scale inversion does not occur is indicated by the circles at 100% transmittance. Taking notice of such brightness or gray-level inversion, transmittance will hereinafter be called gradation.

Figure 6 shows viewing-angle dependence for contrast ratios CR in e mode. Contrast ratio is defined as contrast with the darkest gray-scale level G0 corresponding to the highest applied voltage V7. The left-hand graph shows viewing-angle dependence in the horizontal direction (50) and the right-hand graph shows viewing-angle dependence in the vertical direction (50). For example, in the left-hand graph, the curve V0 shows viewing-angle dependence in the horizontal direction with respect to the ratio of transmittance (gray scale G0) corresponding to voltage V0 to transmittance (gray scale G7) corresponding to voltage V7. Similarly, curve V6 shows viewing-angle dependence in the horizontal direction with respect to the ratio of transmittance (gray scale G6) corresponding to voltage V6 to transmittance (gray scale G7) corresponding to voltage V7. In the right-hand graph, curve V0 shows viewing-angle dependence in the vertical direction with respect to the ratio of transmittance (gray scale G0) corresponding to voltage V0 to transmittance (gray scale G7) corresponding to voltage V7. Similarly, curve V6 shows viewing-angle dependence in the vertical direction with respect to the ratio of transmittance (gray scale G6) corresponding to voltage V6 to transmittance (gray scale G7) corresponding to voltage V7.

Figure 7 shows viewing-angle dependence for contrast ratios CR in o mode. Referring to Figures 4, 5, 6 and 7, the range of viewing angles within which gray-scale inversion does not occur, is indicated by squares at contrast ratio 100. With respect to contrast ratio, one at the brightest level is predominant over others.

Figure 8 permits comparison of the ratios of transmittance (gray scale G0) corresponding to voltage V0 to transmittance (gray scale G7) corresponding to voltage V7 in o mode and e mode. Figure 8 shows that the viewing-angle characteristic of contrast ratio in e mode is superior in hori-

zontal directions. With respect to vertical directions, o mode is superior in the downward direction and e mode is superior in the upward direction.

As indicated hitherto, viewing-angle characteristics for contrast ratio and gradation have both advantages and disadvantages regardless of o or e mode. The viewing-angle characteristic of contrast ratio in e mode is superior in the horizontal directions. However, with respect to the vertical directions, neither mode has good viewing-angle characteristic in the upward direction, and o mode is wholly superior in the downward direction. Therefore, if the downward direction is assumed to be a usual direction, o mode can obtain a better contrast ratio. However, as shown in Figure 5, in the downward direction, particularly with low transmittance, gray-scale inversion occurs, and thus gradation significantly decreases. Conventionally, gradation is sacrificed for contrast ratio to adopt the downward direction as the normal viewing direction. Considering the viewing-angle characteristics of contrast ratio and gradation, contrast ratios are at nearly equivalent level in e and o modes in horizontal and vertical directions, and e mode is inferior to o mode only for gradation in the upward direction. If the upward direction can be used as the normal viewing direction to prevent gray-scale inversion, e mode will have the viewing-angle characteristic of more balanced contrast ratio and gradation than o mode.

Figure 2 shows the relation between applied voltages plotted for each angle in the upward direction and transmittance (the graph is called a V-T curve). The angles vary at a step of 10 within the range from 0 to 50 in the upward direction. For eight-level gray-scale display, voltages of, typically, V0 = 0 volt, V1 = 2.4 volt, V2 = 2.6 volt, V3 = 2.8 volt, V4 = 3.1 volt, V5 = 3.4 volt, V6 = 3.8 volt, and V7 = 5 volt are applied in the ascending order. The applied voltages are set after consideration of predetermined gamma correction based on transmittance at 0 viewing angle. The curve for 0 viewing angle is even until an applied voltage reaches approximately 1.8 volt. The curve then monotonously decreases. Therefore, gray-scale inversion will not occur at 0 viewing angle. The peaks of transmittance occur at the applied voltage of about 2 volt at viewing angles in excess of 20. Therefore, gray scale starts to invert at viewing angles in excess of 20.

In accordance with the present invention, gray-scale inversion is prevented by shifting the lowest applied voltage V0 in the direction in which the above V-T curve monotonously decreases. There are different ways of setting the lowest applied voltage V0. For example, in a preferred embodiment of the present invention, the lowest applied voltage is set to greater than or equal to a voltage corresponding to the maximum in the V-T curve. In another embodiment, the lowest applied voltage is set to less than the voltage corresponding to the maximum in the V-T curve. The V-T curve obtained at a predetermined viewing angle to the direction of a normal line to the display surface of the liquid crystal display may be selected. Alternatively, the V-T curve obtained as a result of integration of the V-T curve between 0 viewing angle and a predetermined viewing angle to the direction of the normal line to the display surface of the liquid crystal display may be selected.

Referring to Figure 2, the peaks (that is, maxima) of transmittance occur at about 2 volts applied voltage in excess of the viewing angles of 20. Therefore, the lowest applied voltage V0 can be set to a voltage (about 2 volt) greater than the voltage corresponding to maximum transmittance. In this case, the applied voltages are set to V0 = 2.0 V, V1 = 2.4 V, V2 = 2.6 volt, V3 = 2.8 volt, V4 = 3.1 volt, V5 = 3.4 volt, V6 = 3.8 volt, and V7 = 5 volt.

Figure 1 shows viewing-angle dependence of transmittance in the horizontal and the vertical directions where the lowest applied voltage V0 is set to about 2.0 volt. In the right-hand graph of Figure 1, dashed line 6 shows transmittance corresponding to the lowest applied voltage with no application of the present invention. Solid line 2 shows transmittance corresponding to the lowest applied voltage with the present invention applied and the lowest applied voltage V0 set to about 2.0 volt. A comparison of the curves 6 and 2 indicates that the threshold at which gray-scale inversion occurs is improved from about 25 to about 40 .

Referring back to Figure 2, applied voltages giving transmittance maxima are nearly equal to one another at every viewing angle (about 2 volt in the example). However, as viewing angle increases, the transmittance peak has a tendency to shift right. Therefore, to prevent gray scale from being inverted at a viewing angle of 50 , the lowest applied voltage V0 must be set to give the maximum transmittance in the V-T curve at a viewing angle of 50 . Therefore, the lowest applied voltage V0 is set to a little more than 2 volt. Alternatively, the V-T curves may be integrated from 0 viewing angle to a predetermined viewing angle (for example, a viewing angle of 50). In other words, all sums of V-T curves are obtained with respect to 0 viewing angle to the predetermined viewing angle. In the V-T curve thus obtained, the lowest applied voltage may be set to the value giving the maximum transmittance. The lowest applied voltage is again set to a little more than 2 volt.

Still referring to Figure 2, in the 0 viewing angle curve, transmittance (that is, brightness) starts to decrease around an applied voltage of 1.8 volt.

Therefore, if the lowest applied voltage V0 is set too high, the maximum brightness at 0 viewing angle, decreases. This is undesirable. To avoid such a decrease, the lowest applied voltage V0 is set to a little less than the voltage giving the maximum in the V-T curve. In this example, the lowest applied voltage V0 is set to about 1.8 volt.

Referring again to Figure 1, solid line 4 shows transmittance corresponding to the lowest applied voltage V0 set to about 1.8 volt. The threshold viewing angle at which at which gray-scale inversion occurs is about 30 . As aforementioned, if the decrease of the maximum brightness at 0 viewing angle is suppressed, the range of viewing angles within which gray-scale inversion does not occur becomes narrow. Nevertheless, the curve 4 is superior to the curve 6 in terms of gradation. To widen the range of viewing angles within which gray-scale inversion does not occur without significantly decreasing the maximum brightness at 0 viwing angle, the lowest applied voltage V0 must be set, as aforementioned, to the voltage giving maximum transmittance in a V-T curve at the limits of the range. If the lowest applied voltage V0 is thus set, the maximum brightness at a viewing angle of 0 will slightly decrease. Therefore, applied voltages V1 to V7 are reset in consideration of brightness and predetermined gamma correction at the lowest applied voltage V0.

Referring now to Figure 9, liquid crystal display apparatus of the present invention comprises a Liquid Crystal Display (LCD) panel 26 in which a plurality of pixels are arranged in a matrix at the intersections of a plurality of data lines and a plurality of scan lines. A data line driver 22 is provided for driving the data lines. A scan line driver 24 is provided for driving the scan lines. A reference voltage circuit 28 is included for supplying reference voltages to data line driver 22. The reference voltages correspond to V0 to V7. The reference voltages are supplied to the data line driver 22. Reference voltage circuit 28 comprises a voltage source V, and resistors R0 to R7 corresponding to the reference voltages V0 to V7, respectively. Resistor R0 is variable. The lowest applied voltage V0 is set by adjusting resistor R0. For example, if the lowest applied voltage V0 is set to about 1.8 volt, as aforementioned, the maximum brightness at 0 viewing angle is decreased slightly. Therefore, the applied voltages V1 to V7 are reset in consideration of brightness and predetermined gamma correction at the lowest applied voltage V0. Therefore, resistors R1 to R7 may be variable. However, it will be appreciated that R0 to R7 each may be designed to introduce a fixed amount of resistance. It will be appreciated also that a temperature compensating circuit may be built into the reference voltage circuit 28 to compensate the thermal characteristic of the threshold voltage in the liquid crystal.

The optimisation of nd will now be described. n indicates anisotropy in refractive index which is the difference between the refractive index for an ordinary ray and the refractive index for an extraordinary ray and d is the thickness of the liquid crystal. nd is a parameter which determines important characteristics of the liquid crystal such as contrast, viewing-angle dependence, etc. Experiment indicates that as nd increases (for example, nd = 0.48um), the gray level G0 decreases dependence on viewing angles or the shift of colour tone decreases in horizontal and vertical directions at 0 viewing angle. As nd decreases (for example, nd = 0.415um), the gray-scale level G7 decreases dependence on viewing angles. nd can be selected according to whether any characteristic is regarded as being important.

It will be appreciated that the present invention hitherto described may be applied to both monochrome display and colour display.

An example of a liquid crystal display of the present invention has now been described. To summarise, the display comprises a liquid crystal display panel (26). A scan line driver (24) addresses scan lines of the panel (26). A data line driver (22) applies a range of different voltages to data lines of the panel (26) to produce different gray scale levels in a gray scale picture. The data line driver (22) comprises a reference voltage circuit (28) for offsetting the range of applied voltages in such a manner that the transmittance of the panel (26) decreases substantially linearly from the lower extreme of the range to the upper extreme. By shifting the lowest applied voltage in the Voltage-Transmittacne curve in the direction of monotonously decreasing area of the V-T curve, brightness or gradation is prevented from being inverted. Thus, advantageously, the liquid crystal display simultaneously provides both good contrast ratios and good gradation at large viewing angles.

Claims

1. A liquid crystal display operable in normally white mode, comprising: a liquid crystal display panel (26); a scan line driver (24) for addressing scan lines of the panel (26); a data line driver (22) for applying a range of different voltages to data lines of the panel (26) to produce different gray scale levels in a gray scale picture;

   characterised in that the data line driver (22) comprises a reference voltage circuit (28) for offsetting the range of applied voltages in such a manner that the transmittance of the panel (26) decreases substantially linearly from

the lower extreme of the range to the upper extreme.

2. A liquid crystal display as claimed in claim 1, wherein the panel comprises a polarising plate having incidence transmission axis parallel to incidence rubbing direction so that an extraordinary ray can be transmitted through the liquid crystal.

3. Apparatus for driving a normally white mode liquid crystal display panel, the apparatus comprising: a scan line driver, connectable to scan lines of the panel, for addressing scan lines of the panel; a data line driver connectable to data lines of the panel for applying a range of different voltages to data lines of the panel to produce different gray scale levels in a gray scale picture;

   characterised in that the data line driver comprises a reference voltage circuit for offsetting the range of applied voltages in such a manner that the transmittance of the liquid crystal display panel decreases substantially linearly from the lower extreme of the range to the upper extreme.

4. A method of driving a liquid crystal display in normally white mode, the method comprising:

   applying a range of different voltages to elements of the display to produce different gray scale levels in a gray scale picture; and

   offsetting the range of applied voltages in such a manner that the transmittance of the liquid crystal decreases substantially linearly from the lower extreme of the range to the upper extreme.

5. A method as claimed in claim 4, comprising setting the lower extreme of the range of applied voltages to greater than or equal to the voltage providing maximum transmittance of the liquid crystal.

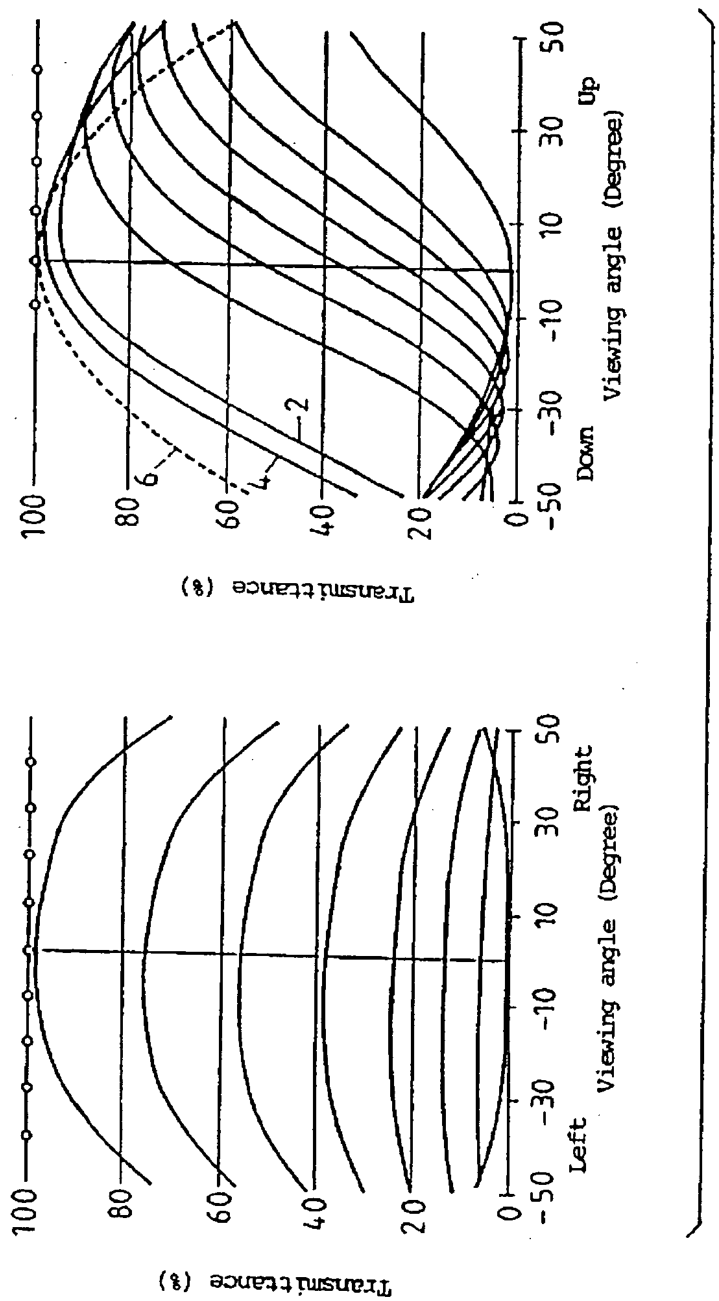
6. A method as claimed in claim 4, comprising setting the lower extreme of the range of applied voltages to less than the voltage providing maximum transmittance of the liquid crystal.

7. In a liquid crystal display apparatus in normally white mode, a method for driving the said liquid crystal display apparatus wherein gray scale displaying is obtained by providing different applied voltages corresponding to different gray scale levels, respectively, characterised in that in a curve showing the relation between said applied voltages and light transmittance (thereafter called V-T curve) the lowest applied voltage is set so as to be shifted in the direction of a monotonously decreasing area of said V-T curve.

8. A method as claimed in claim 7, wherein said V-T curve is a V-T curve for a predetermined viewing angle from a normal line to the display surface of said liquid crystal display apparatus.

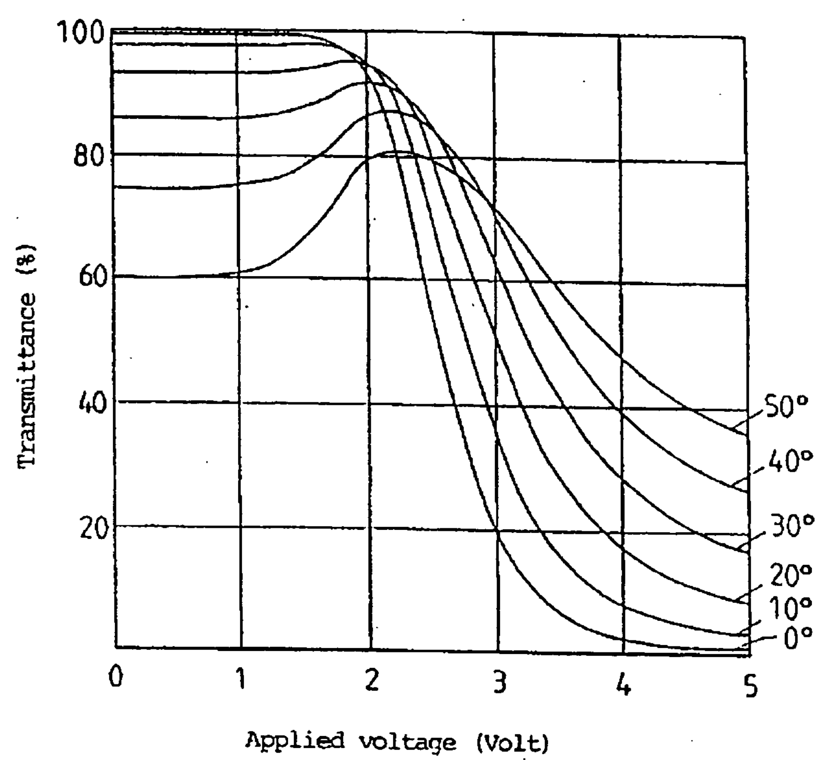
9. A method as claimed in claim 7, wherein said V-T curve is a V-T curve obtained as a result of integration of a V-T curve between the viewing angle of 0 and a predetermined viewing angle from a normal line to the display surface of said liquid crystal display apparatus.

10. A method as claimed in claim 7 or 8, wherein applied voltages other than the lowest applied voltage of different applied voltages corresponding to different gray scale levels, respectively are set, based on said lowest applied voltage, to a monotonously decreasing area of said V-T curve.



Transmittance (%)
100
80
60
40
20
0
-50
-30
-10
10
30
50
Left
Right
Viewing angle (Degree)
Transmittance (%)
Down
Up
2
4
6

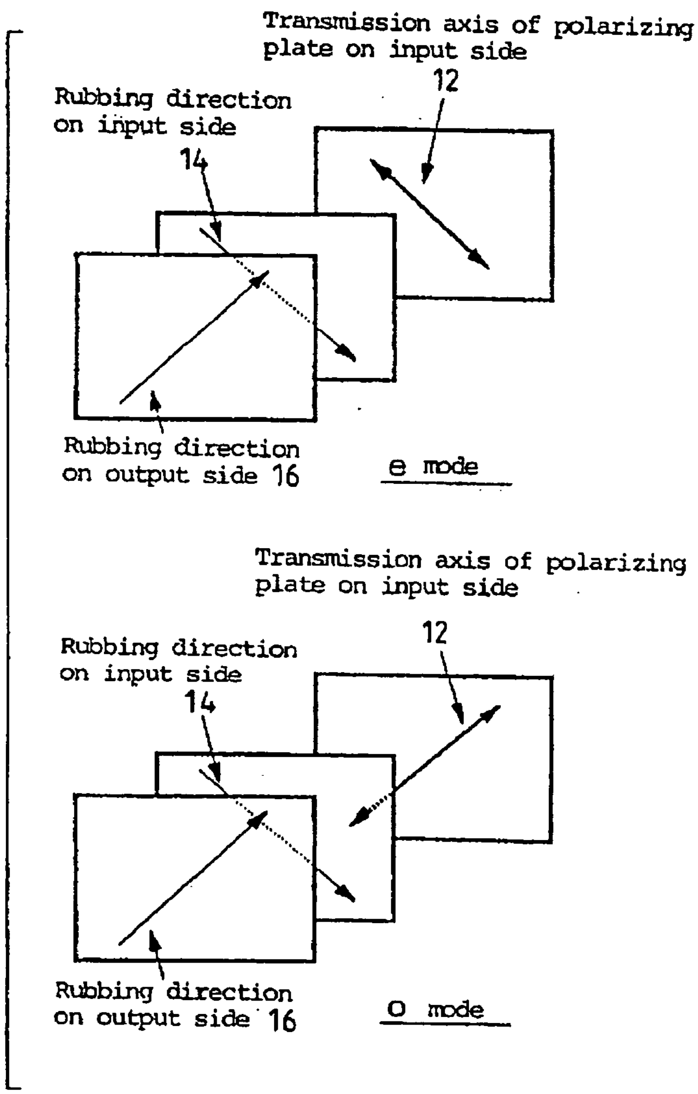
FIG. 1

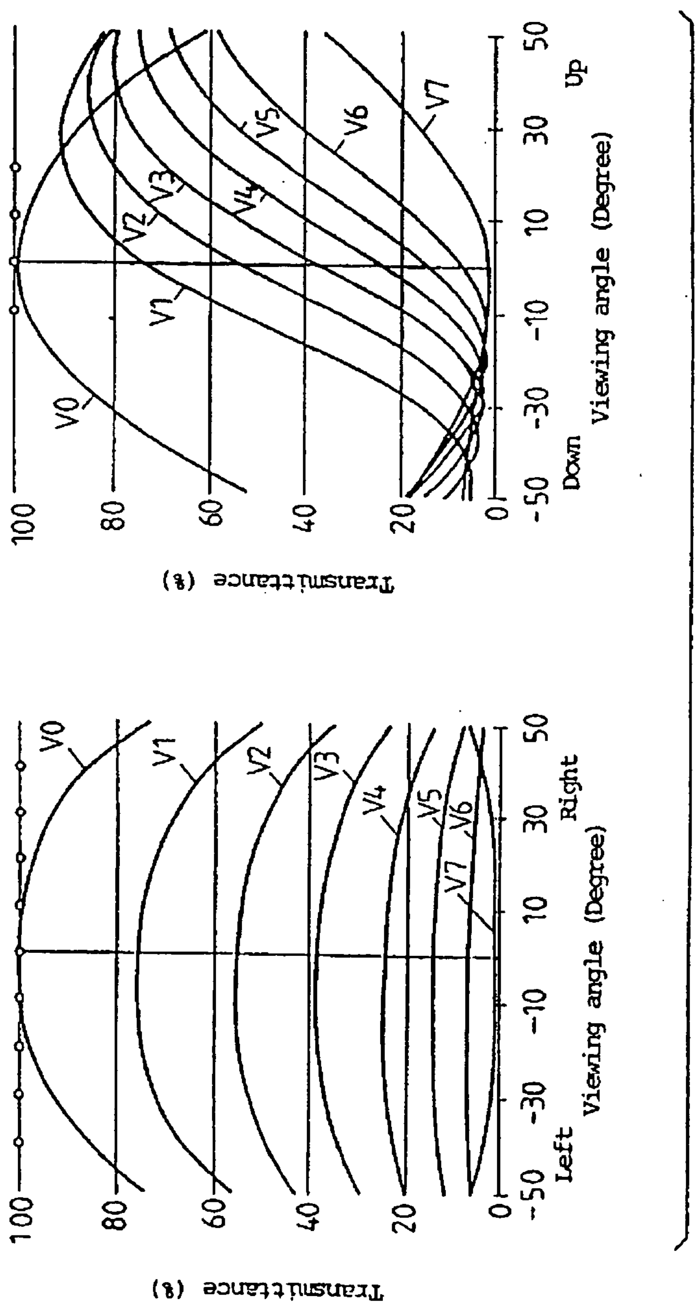


100
80
60
40
20
0
1
2
3
4
5
Transmittance (%)
Applied voltage (Volt)
50°
40°
30°
20°
10°
0°

FIG 2

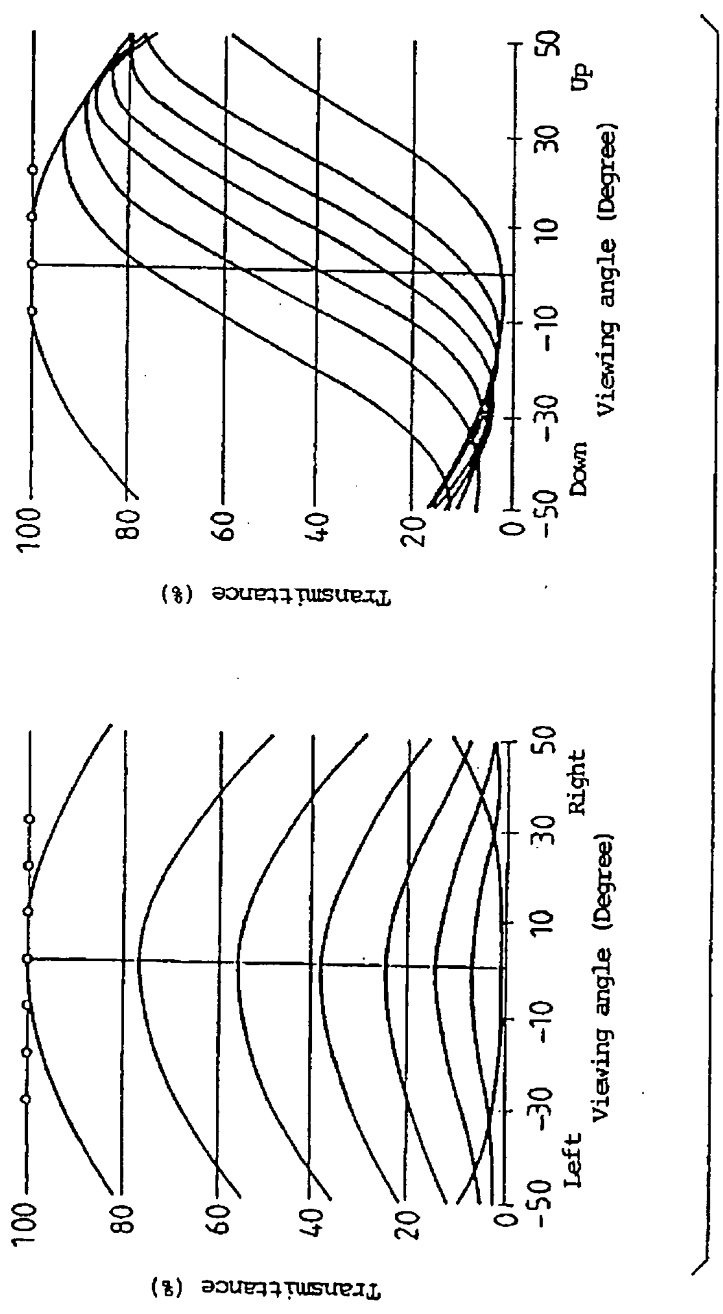
FIG. 3


Transmission axis of polarizing plate on input side
12
Rubbing direction on input side
14
Rubbing direction on output side 16
e mode
Transmission axis of polarizing plate on input side
12
Rubbing direction on input side
14
Rubbing direction on output side 16
O mode



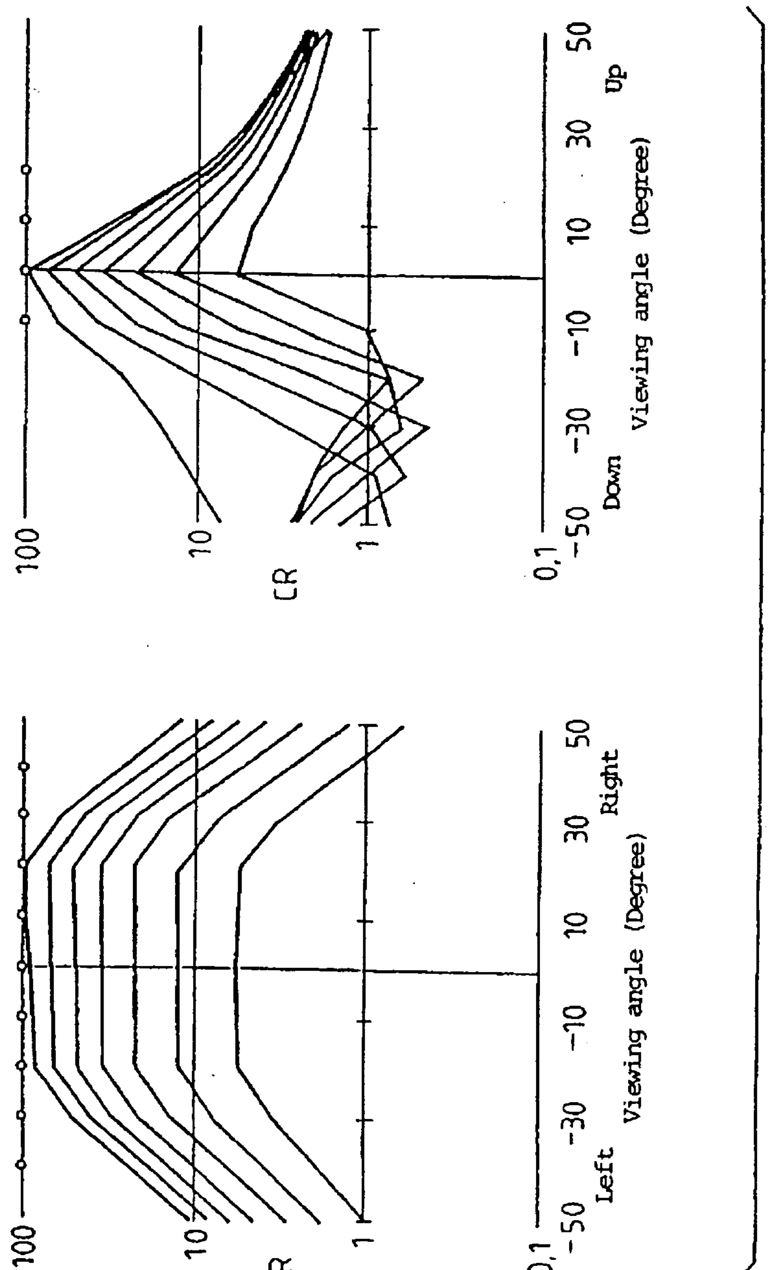
Light transmittance in e mode

FIG. 4



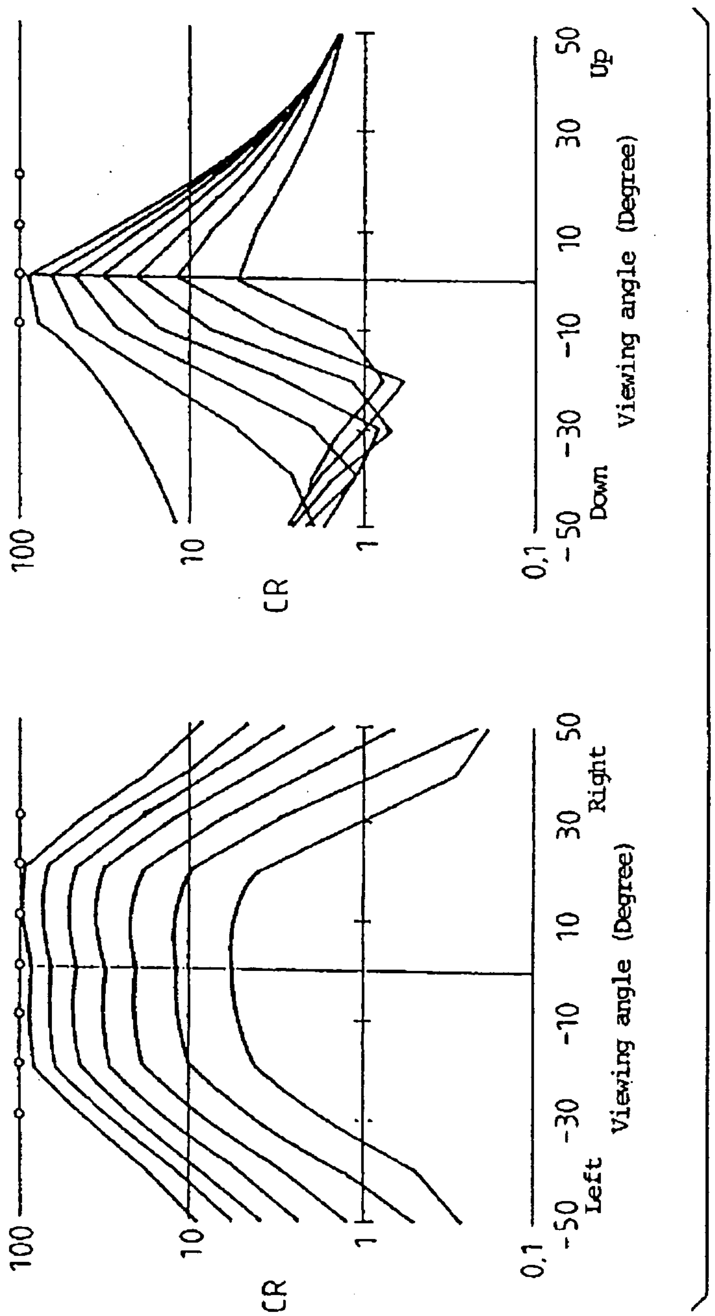
Light transmittance in o mode

FIG. 5



Contrast ratio CR in e mode

FIG. 6



Contrast ratio CR in o mode

FIG. 7

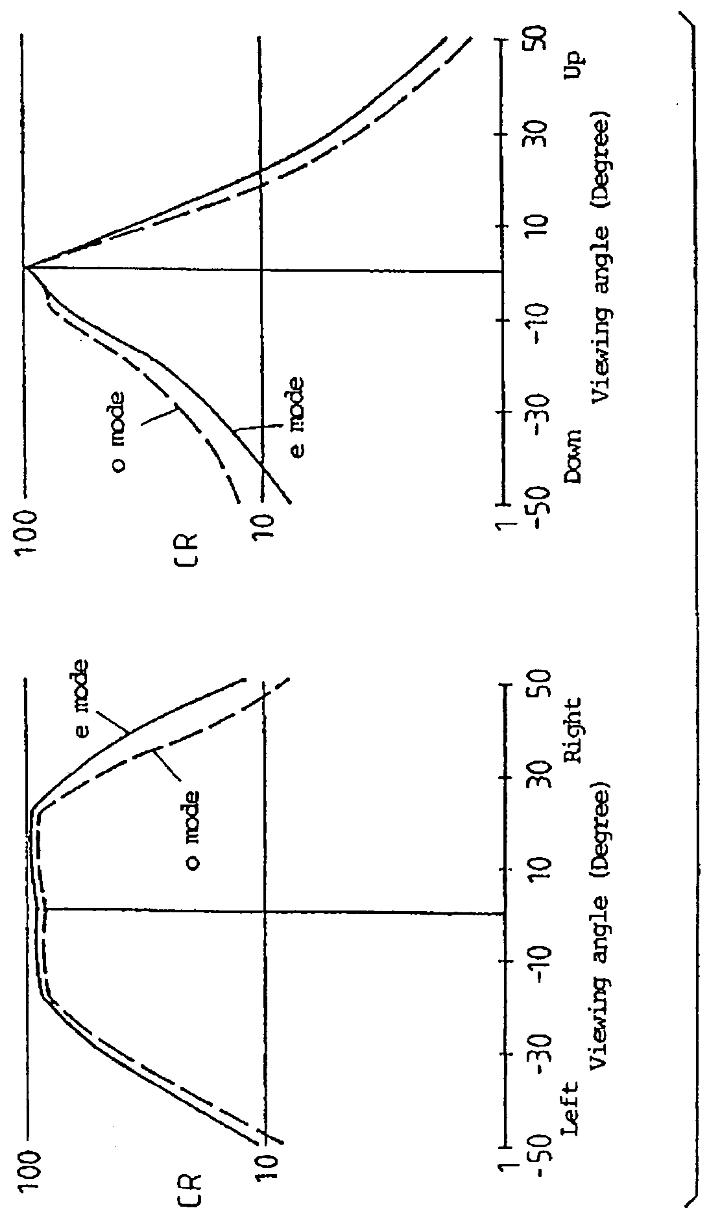

100
CR
10
1
-50
-30
-10
10
30
50
Left
Right
Viewing angle (Degree)
e mode
o mode
100
CR
10
1
-50
-30
-10
10
30
50
Down
Up
Viewing angle (Degree)
o mode
e mode

FIG. 8

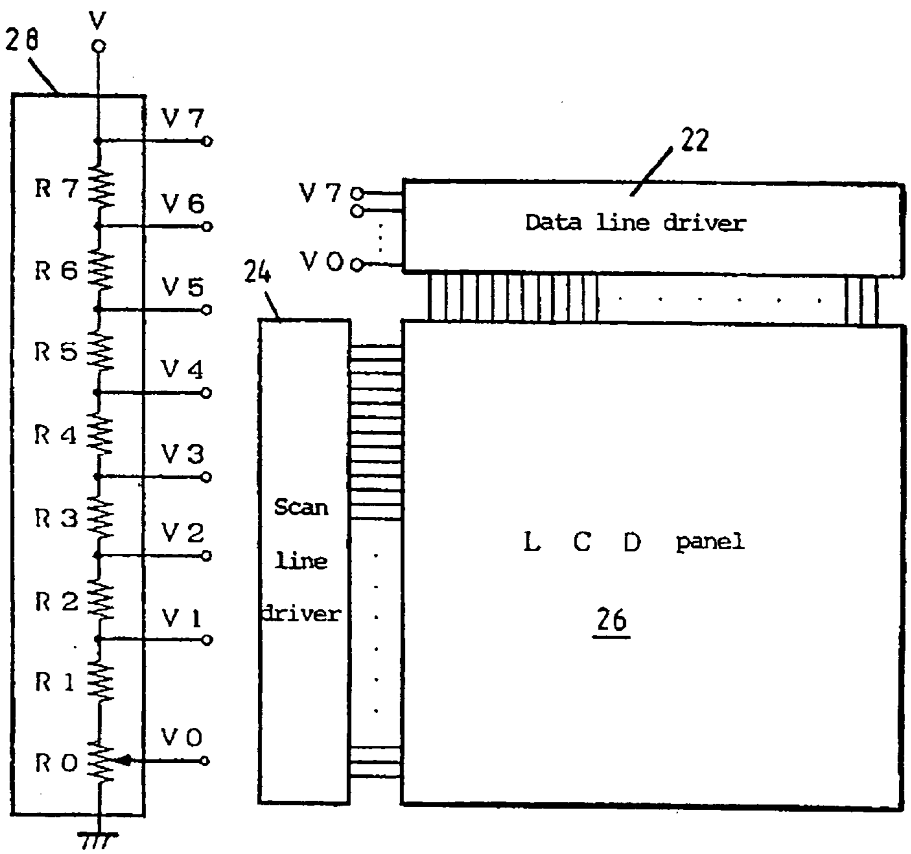

28
V
V7
V6
V5
V4
V3
V2
V1
V0
R7
R6
R5
R4
R3
R2
R1
R0
22
Data line driver
V7
V0
24
Scan
line
driver
L C D panel
26

FIG. 9